Collins Mechanism Contributions to Single Spin Asymmetry

Feng Yuan

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
RIKEN/BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, NY 11973

Abstract. We present recent developments on the single transverse spin physics, in particular, the Collins mechanism contributions in various hadronic reactions, such as semi-inclusive hadron production in DIS process, azimuthal distribution of hadron in high energy jet in pp collisions. We will demonstrate that the transverse momentum dependent and collinear factorization approaches are consistent with each other in the description of the Collins effects in the semi-inclusive hadron production in DIS process.

There have been strong experimental interests on transverse spin physics around the world, from the deep inelastic scattering experiments such as the HERMES collaboration at DESY, SMC and COMPASS at CERN, and Hall A and CLAS at JLab, the proton-proton collider experiment from RHIC at Brookhaven, and the relevant e^+e^- annihilation experiment from BELLE at KEK. In particular, the single-transverse spin asymmetries (SSA), defined as the spin asymmetries when we flip the transverse spin of one of the hadrons in the scattering processes: $A = (d\sigma(S_\perp) - d\sigma(-S_\perp))/(d\sigma(S_\perp) + d\sigma(-S_\perp))$ where $d\sigma$ is the differential cross section, has attract much attention. Great progress has been made in the last few years in exploring the underlying physics for the SSAs observed in various hadronic processes. In this talk, we will present, in particular, the recent developments on the Collins mechanism contribution to the SSAs in hadronic processes. The transverse momentum dependent Collins fragmentation function describes the azimuthal hadron distribution correlated with the quark transverse polarization vector [1]. When combining with the quark transversity distribution, it will generate the SSAs in the semi-inclusive hadron production in deep inelastic scattering (SIDIS) [1] and single inclusive hadron production in pp collisions [2]. It also contributes to the azimuthal asymmetry in di-hadron production in e^+e^- annihilation process [3]. Recent studies have found that the Collins function is universal, meaning that it is the same in the above processes [2, 4, 5, 6, 7, 8]. This contribution is very important not only because it is a significant contribution to the SSA observables in hadronic processes, but also because its contribution is crucial to extract the quark transversity distribution of nucleon, one of the three leading twist quark distributions [9] which is weakly constrained [10, 11]. The experimental investigations of these physics have been recently very active in SIDIS [12] and e^+e^- processes [13]. The TMD quark fragmentation function are defined through the following matrix,

$$\mathscr{M}_h^{\alpha\beta}(z,p_\perp) = \frac{n^+}{z}\int\frac{d\xi^-}{2\pi}\frac{d^2\xi_\perp}{(2\pi)^2}e^{-i(k^+\xi^- - \vec{k}_\perp\cdot\vec{\xi}_\perp)}\sum_X\frac{1}{3}\sum_a\langle 0|\mathscr{L}_0\psi_{\beta a}(0)|P_hX\rangle \times\langle P_hX|(\overline{\psi}_{\alpha a}(\xi^-,\vec{\xi}_\perp)\mathscr{L}_\xi^\dagger|0\rangle\ , \quad (1)$$

where $a=1,2,3$ is a color index, α and β are Dirac indices, and $p_\perp$ is the transverse momentum of the final state hadron with momentum P_h relative to the fragmenting quark k. The quark momentum k is dominated by its plus component $k^+=(k^0+k^z)/\sqrt{2}$, and we have $P_h^+=zk^+$ and $\vec{k}_\perp=-\vec{p}_\perp/z$. For convenience, we have chosen a vector $n=(1^+,0^-,0_\perp)$ which is along the plus momentum direction. The gauge link $\mathscr{L}_\xi=\exp\left(-ig\int_0^\infty d\lambda v\cdot A(\lambda v+\xi)\right)$ is along the direction v conjugate to n [14, 15, 16]. The leading order expansion of the above matrix leads to two fragmentation functions for a scalar meson,

$$\mathscr{M}_h = \frac{1}{2}\left[D(z,p_\perp)\ \not{n}+\frac{1}{M}H_1^\perp(z,p_\perp)\sigma^{\mu\nu}p_{\mu\perp}n_\nu\right]\ , \quad (2)$$

where M is a mass scale chosen for convenience, and the second term defines the Collins function $H_1^\perp$. From the above equation, we can further define the transverse-momentum moment of the Collins function: $\hat{H}(z)=\int d^2p_\perp\frac{p_\perp^2}{2M}H_1^\perp(z,p_\perp)$. By integrating out the transverse momentum, the fragmentation function will only depend on the longitudinal momentum fraction z of the quark carried by the final state hadron. It is straightforward to show that this function can be written as a twist-three matrix element of the fragmentation function,

$$\hat{H}(z) = n^+z^2\int\frac{d\xi^-}{2\pi}e^{ik^+\xi^-}\frac{1}{2}\left\{\mathrm{Tr}\sigma^{\alpha+}\langle 0|\left[iD_\perp^\alpha+\int_{\xi^-}^{+\infty}d\zeta^-gF^{\alpha+}(\zeta^-)\right]\psi(\xi)|P_hX\rangle \times\langle P_hX|\bar{\psi}(0)|0\rangle+h.c.\right\}\ , \quad (3)$$

where we have chosen the gauge link in Eq. (1) going to $+\infty$, and $F^{\mu\nu}$ is the gluon field strength tensor and we have suppressed the gauge links between different fields and other indices for simplicity. Since the Collins function is the same under different gauge links, we shall obtain the same result if we replace $+\infty$ by $-\infty$ in the above equation.

From the above definition, we can see that $\hat{H}(z)$ involves derivative on the quark field and the field strength tensor explicitly, and it belongs to more general twist-three fragmentation functions [17]. For example, extending the above definition, we can define a two-variable dependent twist-three fragmentation function as,

$$\hat{H}_D(z_1,z_2) = n^+z_1z_2\int\frac{d\xi^-d\zeta^-}{(2\pi)^2}e^{ik_2^+\xi^-}e^{ik_g^+\zeta^-}\frac{1}{2}\left\{\mathrm{Tr}\sigma^{\alpha+}\langle 0|iD_\perp^\alpha(\zeta^-)\psi(\xi^-)|P_hX\rangle \times\langle P_hX|\bar{\psi}(0)|0\rangle+h.c.\right\}\ , \quad (4)$$

where $k_i^+=P^+/z_i$ and $k_g^+=k_1^+-k_2^+$. Similarly, we can define a F-type fragmentation function by replacing $D_\perp^\alpha$ with $F^{+\alpha}$. However, the F and D types are related to each other by using the equation of motion [18]. Therefore, they are not independent.

These functions are our starting point to formulate the Collins mechanism in the collinear factorization approach. First, we can calculate the transverse momentum dependence of the Collins function in the perturbative region from the twist-three fragmentation functions $\hat{H}_D$ ($\hat{H}_F$) and $\hat{H}$. To do this, we will have to not only calculate the perturbative diagrams with gluon radiation, but also to perform the twist expansion and take into account full contributions from the $\partial_\perp$ and $A_\perp$ operators in the definitions of $\hat{H}_D$ and $\hat{H}$ at this order [18, 8]. An important check of the above result is its universality property. Indeed, we find that our calculations are independent of the gauge link direction used in Eq. (1). In particular, we find that the gauge link does not contribute to a pole in the Feynman diagrams [8]. Therefore, the gauge links going to $+\infty$ and $-\infty$ lead to the same results, and do not generate sign changes between different processes. This is consistent with the universality argument for the Collins fragmentation function [5, 2]. Because of this, this calculation shall apply to all the processes the Collins function involved. This clearly demonstrates its universality property.

Furthermore, we can also calculate the Collins contribution to the SSA in semi-inclusive DIS, $ep_\uparrow \to e'\pi X$, and show that the TMD and collinear factorization approaches are consistent in the intermediate transverse momentum region $\Lambda_{\rm QCD} \ll P_{h\perp} \ll Q$, where $\Lambda_{\rm QCD}$ is the typical nonperturbative scale and $P_{h\perp}$ is the transverse momentum of the final state hadron. Again, the above defined $\hat{H}_D$ and $\hat{H}$ will be our starting basis to calculate this contribution in the collinear factorization approach. Following the same procedure as that in [19] for the Sivers effects, we find find that the single transverse spin dependent differential cross section for the above process in the collinear factorization approach can be reproduced by the TMD factorization for the same observable [16] by using the large transverse momentum Collins fragmentation function, and the known results for the quark transversity distribution h_1 and the soft factor [19]. This clearly demonstrates that in the intermediate transverse momentum region, the twist-three collinear factorization approach and the TMD factorization approach provide a unique picture for the Collins contribution to the SSA in the semi-inclusive DIS [8].

Besides the above semi-inclusive DIS process, we can also study the Collins contribution to the azimuthal asymmetric distribution of hadrons inside a high energy jet in the transversely polarized pp collision,

$$p(P_A, S_\perp) + p(P_B) \to jet(P_J) + X \to H(P_h) + X \ , \tag{5}$$

where a transversely polarized proton with momentum P_A scatters on another proton with momentum P_B, and produces a jet with momentum P_J. The three momenta of P_A, P_B and P_J form the so-called reaction plane. Inside the produced jet, the hadrons are distributed around the jet axis, where we define transverse momentum P_{hT} relative to the jet axis. The correlation between P_{hT} and the polarization vector $S_\perp$ introduces the Collins contribution to the single spin asymmetry in this process. Again, we can perform the calculation of this asymmetry, and find that the same Collins function as that in the semi-inclusive DIS. The key steps in the universality derivation are the eikonal approximation and the Ward identity. The eikonal approximation is valid when we calculate the leading power contributions. The Ward identity ensure that when we sum up the diagrams with all possible gluon attachments we shall get the eikonal propagator from the gauge link in the definition of the fragmentation function. The most important point to apply the Ward identity in the above analysis is that the eikonal propagator does not contribute to the phase needed to generate a nonzero SSA.

This observation is very different from the SSAs associated with the parton distributions, where the eikonal propagators from the gauge link in the parton distribution definition play very important role. It is the pole of these eikonal propagators that contribute to the phase needed for a nonzero SSA associated with the naive-time-reversal-odd parton distributions, which also predicts a sign difference for the quark Sivers function between the SIDIS and Drell-Yan processes.

In conclusion, recent studies have demonstrated that the transverse momentum dependent and collinear factorization approaches are consistent for for describing the Collins contribution to the semi-inclusive DIS process in the intermediate transverse momentum region. We have also demonstrated that the Collins fragmentation function calculated is universal. This development shall stimulate similar calculations to the Collins contributions to the SSAs in other processes, such as in hadron production in polarized pp scattering and di-hadron correlation in e^+e^- annihilation.

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